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SMALL-SCALE EXPERIMENTS ON SPLITTING OF ICE FLOES

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ABSTRACT

When small-scale indentation tests were conducted by pushing a flat, vertical indentor against the edges of floating freshwater ice sheets at low velocities, a macrocrack always formed in front of the indentor. When the indentor was made to impact against free-floating ice floes at high velocities, the floes did not split. The difference in these results is attributed to the different modes of ice deformation at different indentor velocities relative to ice. For low velocity tests, the ratio of crack opening force to ice pushing force is estimated from experimental data and existing theoretical results in the literature.

INTRODUCTION

Impact of drifting ice floes against fixed structures is a common occurrence. This interaction often results in splitting of the ice floes. At the time of river ice breakup in 1982 and 1983, I observed drifting ice floes about 1 m thick and moving at a speed of 2 m s^{-1} in the Yukon River impacting against the 2.75-m-wide piers of the bridge carrying the trans-Alaska pipeline. During an interaction with very large floes (600 × 600 m), the ice crushed continuously against the piers for a long period of time without splitting. When small-size floes (5 × 5 m) impacted the piers, they simply rebounded and drifted away without crushing or splitting. But the intermediate-size floes (100 × 100 m) crushed initially against a pier and then split as a result of propagation of a crack from the zone of crushing.

For estimating ice forces on structures, it is important to understand the mechanism of splitting of ice floes because the loads can be considerably lower if splitting takes place. Among the many scenarios of ice action against an offshore structure in the Arctic, the impact from large, thick, multiyear ice floes in the summer open water season is an important one.

Splitting of multiyear floes has been observed in the field (Danielewicz and Metge, 1981, 1982; Danielwicz et al., 1983; and Danielwicz and Cornet, 1984). Initial theoretical studies on the splitting of ice floes by Palmer et al. (1983) were based on the ceramics literature (Kendall, 1978; Lawn and Swain, 1975; Lawn et al. 1980). Further theoretical studies were presented by Bhat (1988) and Bhat et al. (1989). Though the results of theoretical studies are encouraging, experimental verification of these results has been practically nonexistent.

The objective of this paper is to discuss the results of two sets of small-scale experiments: indentation tests on constrained ice sheets at low velocities and impact tests on free-floating ice floes at high velocities. During the indentation tests, a macrocrack always formed in front of the indentor, which might have split the ice sheet if it were not frozen to the basin walls. During impact tests, the free-floating ice floes did not split apart. The reasons for the difference in these results will be discussed.

EXPERIMENTAL SETUP, PROCEDURE AND RESULTS

All experiments were done with freshwater, columnar ice, which was grown by seeding with a spray of water and air mixture over the water surface and growing the ice sheet at an ambient temperature of about –20°C. The ice thickness ranged from 14 to 60 mm.

Indentation tests were conducted by pushing flat, vertical indentors of three different widths (50, 100 and 150 mm) against the edges of floating, confined ice sheets at different velocities. The experimental setup for indentation tests is shown in Figure 1 (Nakazawa and Sodhi, 1990). The assembly containing the indentor was mounted under the carriage that spans the basin. The displacements of the carriage and of the indentor were measured separately with respect to a fixed datum. The range of indentation velocities was from 1 to 9 mm s^{-1}.

During the indentation tests, indentors were pushed against a 7-m-long and about 35-m-wide ice sheet as shown in Figure 2. The indentor was located at a distance of 5 m from a previous track and made to indent into an uncracked portion of ice. During a typical test, the transparent ice would turn milky with microcracks in front of the indentor. As the interaction force increased during microcracking and deformation of the ice sheet, one (and sometimes two) radial macrocracks were observed to propagate suddenly into the ice sheet ahead of the indentor. The instant the macrocrack propagated was noted by manually pressing a button, which sent an electric signal to the data acquisition system for

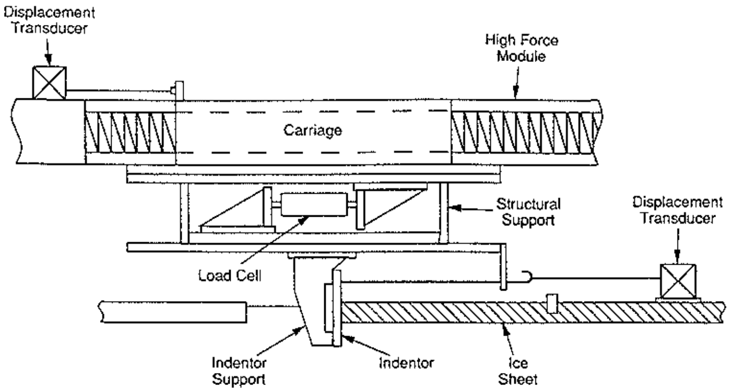

Fig. 1 Experimental setup for indentation tests.

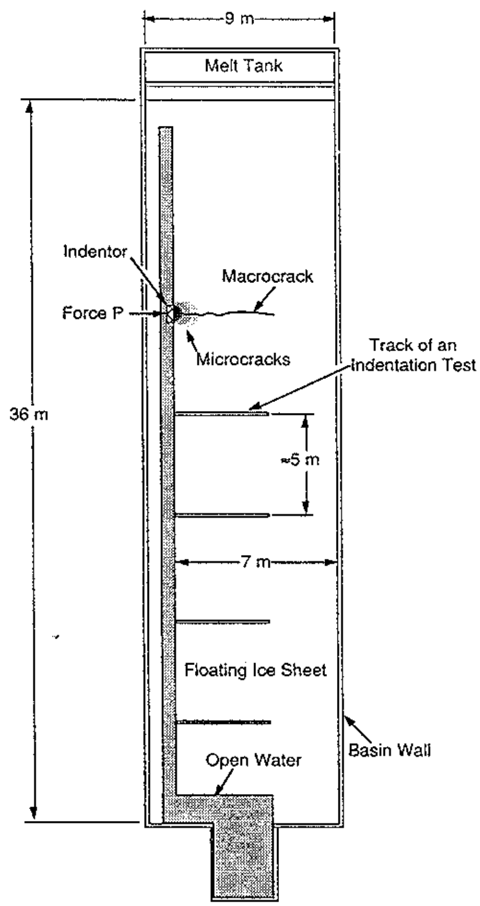

Fig. 2 Sketch of the test basin showing the size of ice sheet indented, formation of microcracks near the indentor and the propagation of a macrocrack from the zone of indentation.

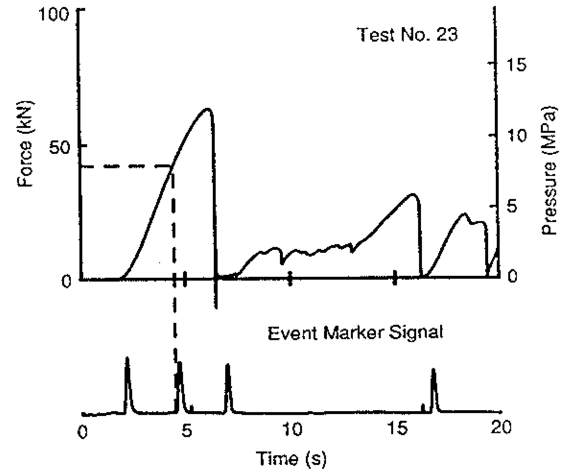

Fig. 3 Records of force and event marker signal for a typical test. The indentor width was 100 mm, the ice thickness 53 mm and average indentation velocity 4.6 mm s^{-1}. Scale on the right indicates the effective pressure. The dashed lines indicate the instant and the force level at which a macrocrack propagated.

Table 1. Values of ice thicknesses t, indentor width d, average indentation velocity v, and the measured forces P for propagation of a macrocrack.

Test no.	t (mm)	d (mm)	v (mm s^{-1})	P (kN)
22	57	100	2.9	41.1
23	53	100	4.5	42.6
24	55	100	3.0	31.6
25	56	100	1.5	28.4
26	55	100	1.4	31.5
43	60	50	5.1	21.9
45	56	50	4.6	36.2
47	57	50	1.9	25.2
49	60	50	1.1	16.5
51	33	100	8.9	29.4
52	34	100	6.8	25.2
63	56	100	6.6	33.9

simultaneous recording of the event with other data on forces and displacements. A typical force and event-marker signal is shown in Figure 3. The scale on the right side of Figure 3 shows the effective pressure, which is defined as the interaction force divided by the contact area (thickness × width). From these records, the magnitude of the force at the instant of crack propagation was found. Because of manual operation of the event marker, there is some room for error in determining the force at the time of crack propagation. The values of ice thickness, indentor width, average indentation velocity and the force for crack propagation measured during different tests are given in Table 1. A discussion on these results will be presented later.

Small-scale experiments on floe splitting were done by impacting a free-floating ice floe with an indentor mounted on the carriage, as shown in Figure 4. The indentor was made to move at a high velocity (0.5–1.0 m s^{-1}) to get some crushing and indentation of the ice floe. The indentor width was 150 mm. The situation represented in these tests is that of "replica" modeling, in which the properties of the material (freshwater ice, in this case), the stresses, and the velocities are the same as those in the actual conditions, and splitting behavior of ice floes is expected to represent that behavior.

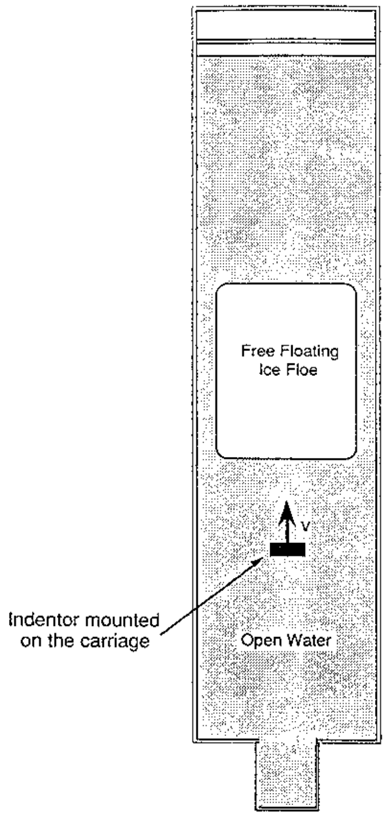

Fig. 4 Sketch of free-floating ice floe being impacted by an indentor moving at a velocity v.The floe size and impact velocity are given in Table 2. The width of the impacted floe was 8–8.5 m.

Table 2. Values of ice thickness, impact velocity floe size and observations during impact tests. Indentor width in all tests was 150 mm.

Test no.	Thickness (mm)	Velocity (m s^{-1})	Floe size (m × m)	Observations
6	32	0.5	4.3 × 8	No splitting
7	32	1.0	4.3 × 8	Some indentation
8	32	1.0	3 × 8	Floe submerged
9	22	0.5	28 × 8	Some indentation
10	22	1.0	28 × 8	35-cm indentation
11	22	1.0	24 × 8	40-cm indentation
12	22	1.5	24 × 8	45-cm indentation
13	16	1.0	25 × 8.5	Some fragmentation
14	16	1.0	5.5 × 8.5	Floe submerged
15	16	1.5	11.5 × 8.5	20-cm indentation
16	14	1.0	26 × 8.5	3.8-m-long crack
17	14	0.5	18 × 8.5	3-cm indentation
18	14	0.5	10 × 8.5	2-cm indentation
19	14	0.5	10 × 8.5	No splitting

These tests were conducted on four ice sheets. The thicknesses and the sizes of ice floes used in different tests are listed in Table 2 along with the relative velocity of the carriage with respect to a floe before impact. Though there was some indentation of the ice floes, not a single floe completely split apart. Sometimes radial cracks were observed near the area of indentation, as shown in Figures 5 a–c. A typical ice force record obtained from these tests is shown in Figure 6, in which a scale for the effective pressure is also given on the right-hand side of the plot. It can be seen from Figure 6 that the effective pressure during the interaction

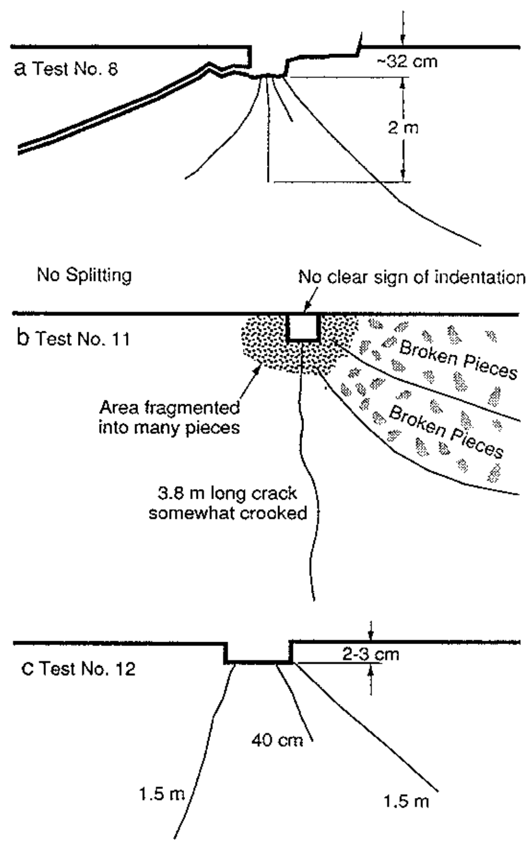

Fig. 5 Sketches of crack formation in a floe near the area of impact, (a) Test 8, (b) Test 11 and (c) Test 12.

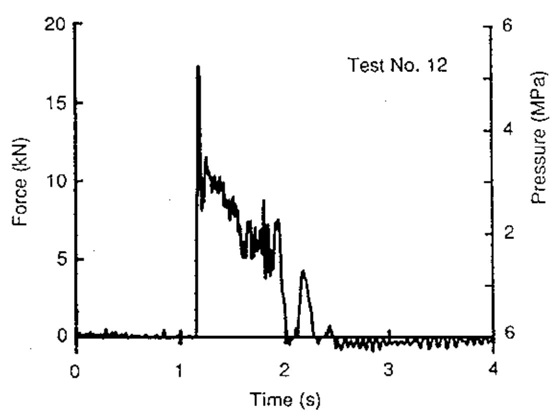

Fig. 6 Typical record of force-time history. The particulars of test 12 are given in Table 2. Scale on the right indicates the effective pressure for that test.

was about 2–5 MPa, whereas it was in the range of 8–12 MPa during indentation tests at low velocity (Fig. 3).

DISCUSSION

Before we discuss the differences in the results between the two sets of experiments, it will be useful to discuss briefly some of the results of previous indentation tests conducted by Sodhi (1991a,b). One of the results of those indentation tests was the effect of carriage velocity on the mode of ice–structure interaction and the effective pressure. At low carriage velocities (< 1 mm s^{-1}), there were no structural vibrations, and creep deformation of ice took place with extensive microcracking. At intermediate carriage velocities (10–120 mm s^{-1}), the ice failed intermittently, resulting in structural vibrations. At high carriage velocities

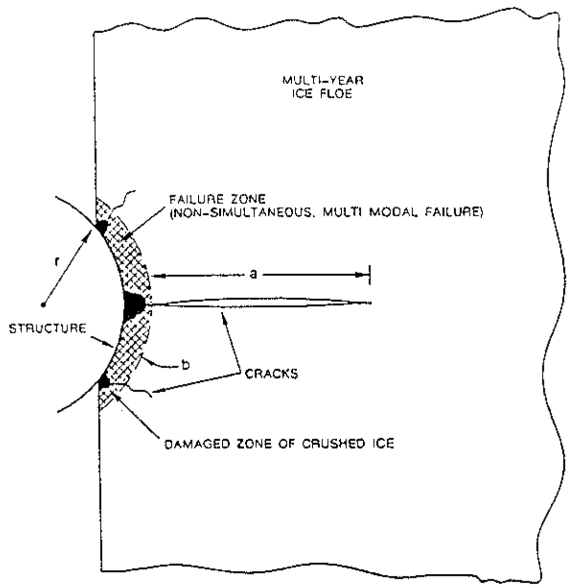

Fig. 7 Sketch showing the formation of microcrack in front of the indentor, leading to development of crack opening force in addition to ice force (from Bhat, 1988).

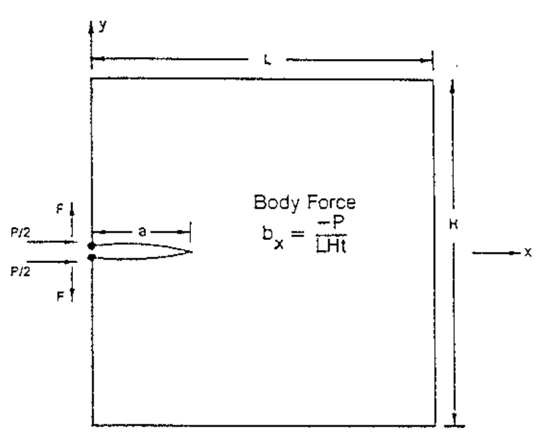

Fig. 8 Sketch of an ice flow with a crack of length, a, and crack opening force F and ice force P (from Bhat, 1988).

(> 120 mm s^{-1}), the ice crushed continuously, resulting in low effective pressure. During continuous crushing, there was little microcracking in the ice sheet and practically no structural vibration. The reduction in effective pressure during continuous crushing is attributed to the change in failure mode from in-plane deformation of ice at low velocity to out-of-plane deformation of ice at high indentor velocities.

The major differences between the two sets of experiments described in this paper are the relative velocity of indentation and the confinement imposed on the ice sheet. When there was confinement on the ice sheet being indented at low velocity, a crack formed every time the test was conducted. Such a crack would have split apart the ice sheet into two pieces if the ice sheet had not remained frozen to the basin wall. During the impact experiments at high relative velocity, the unconfined floes did not split apart, and the effective pressure was low compared to that during the indentation tests. This suggests that the failure modes during the two sets of experiments were different: in-plane deformation of ice during indentation experiments leading to formation of a macrocrack, and out-of-plane brittle failure of ice during the impact tests leading to very little splitting force. Alternatively, it can be said that the crack-opening force during the impact tests did not reach a critical value to propagate an unstable crack.

For the propagation of a macrocrack, one needs to address two issues: nucleation and propagation. When an indentor pushes against the edge of an ice sheet, an area of damaged ice, full of microcracks, forms in front of the indentor (Fig. 7). The state of stress in this area is almost hydrostatic compression, which results in crack opening force F and ice pushing force P as shown in Figure 8. The force F is assumed to be proportional to P, i.e., $F = \beta P$. Using linear elastic fracture mechanics (LEFM), Bhat (1988) has presented the results of a finite element analysis in terms of nondimensional crack opening force $F/(tK_I\sqrt{L})$ vs. nondimensional crack length $\alpha(= a/L)$, where K_I is the crack tip stress intensity factor, L, the floe length and, a, the crack length.

Because the ice sheet was frozen to the wall and not a square floe (Fig. 2), the nondimensional crack opening force is expected to increase from zero (similar to that of a square floe) for small values of α. For higher values of α, the nondimensional crack opening force will reach a maximum value, decrease and then increase again as the crack tip approaches the basin wall. The plot of expected nondimensional crack opening force is shown by a line in Figure 9.

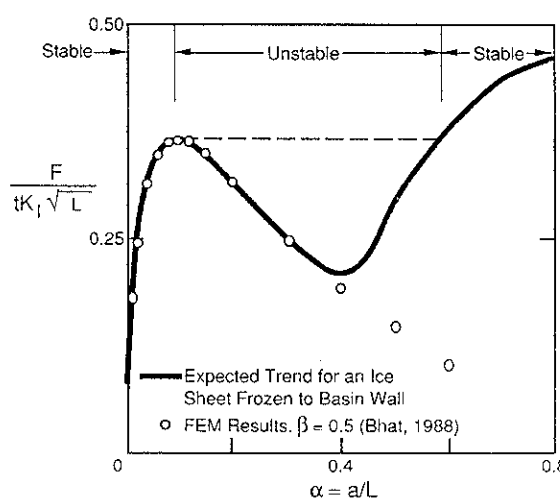

Fig. 9 Plot of nondimensional crack opening force ($F/tK_I\sqrt{L}$ vs. nondimensional crack length a/L (from Bhat, 1988).

Before an indentation, it may be expected that the ice sheet has flaws of the size of a grain. As the interaction force P increases from zero during the indentation, the crack opening force F required to propagate a crack is small, and the initial flaw will grow incrementally in a stable manner. When the crack length reaches a value beyond which the crack opening force starts to decrease (Fig. 9), the crack growth will be unstable until it can feel the effects of the basin wall, which is represented by an increasing value of nondimensional crack opening force in Figure 9. From the above arguments, it can be concluded that the crack grows from a microscopic flaw in ice to a certain length in a stable manner and then grows in an unstable manner. The zones of stable and unstable crack growth are shown in Figure 9 for an increasing ice force P. This is a situation that occurred during the indentation tests, where the cracks suddenly formed to a certain length, but not all the way to the basin wall. The expected trend of nondimensional crack opening force shown in Figure 9 is based on this observation and not on any theoretical or numerical analysis. It is interesting to note that the propagation of macrocracks did not coincide with any drop in the interaction force. This is attributed to the crushing failure of the confined ice sheet.

CONCLUSION

Two sets of small-scale experiments were conducted: indentation at low velocities and impact of free-floating ice floes at high velocities. A crack always formed during indentation tests, but the free-floating ice floes did not split when impacted by a fast moving indentor attached to the carriage. The reasons for the difference in results is attributed to the different modes of ice deformation at different indentation velocities. At high indentation velocities, the crack opening force did not develop to a level to cause unstable crack growth.

It is important to note that during low-velocity indentation a macrocrack propagated suddenly even when no crack was cut in the ice sheet prior to indentation. Though theoretical reasons for unstable crack growth have been provided here, further theoretical and experimental studies are needed to investigate this problem.

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